Title	***Research and Development for a New Paradigm in Nanopositioning and Focusing Mechanics***			
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Date	03/28/2008			
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Category	x-ray science enablers			
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Description:

Start Year (FY)	**2008**	**Duration (Yr)**	**5**

Objectives:

We propose a research and development plan to expand and further nanopositioning techniques to enable novel x-ray optics to achieve spatial resolutions of 10nm and less at the APS. Nano level x-ray science drivers require higher spatial resolution positioning devices and more beamline stations [1, 2]. Our objectives are to develop novel positioning systems for x-ray nanoprobe, nanotomography, coherent diffraction imaging, and ptychography techniques that overcome the limitations of current nanopositioning designs and make the devices more robust and readily available. The specific objectives are to:

- synthesize new types of miniature, fast, stable and elegant nanometer and sub-nanometer x-ray positioning systems through the leveraging of current and near-horizon nanopositioning techniques,
- integrate low-noise, high-bandwidth, actuation, sensing and control into the positioning system, thereby enabling better control and more throughput in more environments than the current systems,
- establish the engineering infrastructure to analyze and test nanopositioning devices,
- build a prototype of a new actively compensated nanotomography rotation stage, and
- build a prototype of a new linear nanopositioning mechanism and incorporate it into a multi-axis scanning stage.

Benefit:

The benefits of pursuing this work include:

- the development of nanopositioning systems that can exploit the higher spatial resolutions obtainable with upcoming nanofocusing techniques such as multilayer Laue lenses, kinoform lenses and lensless techniques [3-5],
- the development of low-runout, high rotation rate tomography stages,

- the enabling of nano x-ray techniques on a more widespread basis because of the compact size and robustness of the proposed designs,
- an increase in the number of nano-capable endstations, and
- the continued growth of in-house innovation in the area of x-ray nanopositioning instrumentation.

Risks of Project: See Note [2]

The project doesn't pose any operational risk to APS systems. However, there is the reasonable risk associated with the investment of effort and money in pursuit of this program. The risk is mitigated in three ways:

1. We propose to take a graded approach, by developing improved state-of-the-art devices on our way to subnanometer positioning.
2. The effort to attain new levels of nanopositioning will inevitably bring about new understanding of the techniques.
3. The activity will open new avenues of collaboration within the APS and between the APS and other facilities, such as NSLS-II and ESRF.

Consequences of Not Doing Project: See Note [3]

If this science driven nanopositioning R&D project is not pursued, the following repercussions may be incurred:

- The current state and approach to nanopositioning at the APS is insufficient to move x-ray science forward and answer the needs of scientists [2].
- The APS will not continue to develop in-house expertise in the area, forcing x-ray scientists to look to external sources for engineering solutions and instrumentation.
- The APS will pass its leadership role in x-ray nanopositioning to ESRF and NSLS-II. [6-10]
- The user community will be underserved, as many nanoprobes are oversubscribed by factors of 2-3 [2].

Cost/Benefit Analysis: See Note [4]

The estimated non-effort cost of this project is approximately $350K, spent over a five year period. The average yearly investment of about $70K could keep the APS at the front of nanolevel x-ray science.

Description:

The design of nanometer level positioning devices is not just a mechanics problem but a multidisciplinary project [11]. A close collaboration between controls engineers and mechanical engineers is required to design and develop the sophisticated mechanics and control mechanisms for the novel nanopositioning devices that we propose. Our approach is two-fold: 1) develop new types of mechanics, not limited by current x-ray nanopositioning concepts, and 2) develop more sophisticated control schemes that move past basic PID control in order to achieve the static and dynamic stability required for routine high-bandwidth positioning at the nanometer and sub-nanometer level. Our recent reviews indicate insufficient consideration of the control side for x-ray nanopositioning

[3, 8]; whereas the coupling between mechanism and control design is a recognized necessity in more mainstream nanopositioning fields [11]. Effective nanopositioning is a union of structure, actuation, sensing, and control. Our research will build a new paradigm in nanopositioning by considering new (to x-ray science) structural designs, new actuator modalities, new sensing modalities, and new control schemes.

Our research plan involves three major steps. The first step in our research plan is to assemble the engineering resources needed to analyze and test nanolevel positioning devices. These resources consist of knowledgeable staff, a mechanically and thermally quiet test cell, and linear and rotation motion metrology equipment. The second step is to use the metrology system to evaluate cutting edge linear and rotational motion technologies. The third and final step is to design and prototype three nanopositioning systems: 1) a state-of-the-art 10 nm accuracy linear motion system, 2) a next generation rotation stage with <50 nm of runout, and 3) a next-generation, <1nm motion system.

<u>Step 1</u>

In accordance with our first step, the collaborative group of staff is currently being formed. Two engineers from the Mechanical Engineering and Design Group (MED) have formed the core of the R&D team. Each of these engineers has experience designing and modeling precision motion devices. Each engineer also has research experience in the measurement, modeling and control of piezoelectric and magnetostrictive mechanisms.

The test cell will be a key component through out the R&D project. The cell consists of a table structure mounted on a STACIS 2100 active vibration isolation system [12]. An acoustic and thermal isolation barrier will surround the table but be mechanically decoupled. While simple in function, the isolated table system is important for three reasons: to provide a quiet environment for device testing, to serve as a prototype for beamline installations, and to duplicate the beamline vibration environment. The STACIS actuators can be used as intelligent shakers to replicate any beamline vibration profile. In fact the engineering team is currently exploring the optimal design for the actively isolated table—bottom mounted isolators supporting a massive table, or top mounted isolators on top of a light and stiff support structure.

The evaluation and subsequent acquisition of suitable metrology equipment rounds out the first step in the R&D process. The sub-nanometer metrology equipment is important for two reasons: 1) to measure the behavior of the nanopositioning devices and 2) to be eventually incorporated as the sensing modality in the operating nanopositioning devices. One task is to evaluate and select an appropriate laser interferometery based linear motion sensor. Laser based sensors are a key technology for high accuracy, large-dynamic range measurement. When compared to other displacement sensing modalities, laser based techniques have higher resolution than a grating encoder and much larger dynamic range than capacitive probes. While the Laser Doppler Displacement Meter (LDDM) is the state-of-the-art for x-ray nanopositioning, the Polytec Laser Doppler Vibrometer (LDV) may offer lower noise and a simpler optic path as compared to the LDDM [14]. However, during our evaluation we intend to compare the LDV to other interferometers such as the Zygo DMI. In addition to linear measurement devices, instrumentation for the measurement of precision spindles will also be evaluated. The device we are considering is the Lion Precision spindle analyzer with non-contact capacitive sensors [15].

Step 2

Our second step is small, but critical: to use the test cell and metrology instrumentation assembled in step one for the evaluation of existing high-precision linear and rotational stages. Manufactures' specifications for nanopositioning equipment are insufficient when trying to design a multi-axis system. The specifications do not detail stiffness, motions orthogonal to the travel axes, and dynamic effects. We will purchase or obtain demonstration units to investigate these unspecified behaviors. This will be done specifically for a long-travel (25mm), high precision ultrasonic motor stage and a commercially available high-precision air bearing rotation stage. This work will lay the groundwork for the 10 nm x-ray scanning device, precision tomography stage, and our novel sub-nanometer stages.

Step 3

Practical x-ray nanopositioning devices will be the product of the initial stages of the third step. We believe that commercial technology has matured and state-of-the-art x-ray nanopositioning (10 nm accuracy) can be obtained through the synthesis of commercial positioning, sensing, and control technologies into an affordable and scalable x-ray nanopositioning system. Commercially available piezo ultrasonic motor stages such as those from Nanomotion or PI, offer large travel ranges with a precision of in the 10 nm range [16, 17]. We intend to overcome the accuracy limitations of these devices through the adaption of laser based position measurement devices, such as the LDV or another interferometer. Configured in linear motion or parallel kinematics configurations, the combination of commercial ultrasonic motor devices, commercial feedforward controllers, and LDV position sensing may offer better than 5 nm accuracy. This level of accuracy may be had at reduced cost, complexity, and mass as compared to the current coarse-fine, dual stage, weak-link mechanisms. Once the concept has been tested in the initial proof of concept, the product of our work would be a six axis x-ray scanning probe device.

Development of a nanotomography rotation stage with <50 nm of radial runout and wobble is the goal for the next part of step three. The specification is mostly based on the desired object feature size. Though, tomography experiment geometry, and detector pixel size play a role too [18]. This specification is similar to instrument development goals set at other facilities [3]. Commercial air bearing stages such as those from Aerotech [19] and Professional Instruments Company [20] have specifications of >100nm of run out. These performance specifications are likely at the current limits obtained with precision machining and balancing. In addition the performance of these devices may be limited by the static stiffness of the air bearing. We propose to purchase the best available rotary air bearing stage and use six high-precision capacitive transducers to quantify the performance. Using the knowledge we gain from the air bearing stage measurements, we will design a compensated rotation stage. We are considering two options: 1) a stationary, 5 degree-of-freedom stage to actuate the rotation stage axis, as other researchers are pursuing [21], or 2) a small, low mass stage mounted on the rotation stage to compensate the stage errors. The integrated system will build on the linear motion experience gained in the first part of step three.

The culmination of step three is where novel advancements in x-ray nanopositioning capability at the APS will enable scientific gains through the use of next generation x-ray focusing optics. Expected foci of kinoform and multilayer Laue lenses are on the 1 nm scale [3, 5]. The resolution and stability of a scanning probe instrument should be 0.1 nm or less to take advantage of these optics. While commercial sub-nanometer positioners exist, such as those for STEM or SEM [22], these unencoded mechanisms only operate over a range of tens of microns. X-ray scanning and focusing applications require tens of millimeter travel ranges to account for sample positioning and changing focal length.

While the path to state-of-the-art nanopositioning (10 nm resolution) involves the use of commercially available technology, the path to next generation nanopositioning (<1 nm resolution) necessitates in-house research and development. This R&D effort covers the five areas necessary for nanopositioning: environment, mechanics, sensing, actuation, and control. The effort is build upon the previously outlined state-of-the-art portion of this work. A summary of the specific R&D tasks in each area are:

Environment

- *Status*: Current designs use passive vibration isolation coupled with large, massive granite supports. The thermal response is controlled with a basic enclosure.
- *R&D efforts*: We see active vibration control as an avenue for an improved vibration environment at the nanopositiong instrument. This can come about by the direct leveraging of existing active vibration control devices, such as the STACIS 2100 [12]. Our R&D efforts center on the optimal way to incorporate the isolators—as the first element in the support structure or higher in the structure, closer to the instrument center-of-mass. In addition to the passive thermal enclosure, active thermal control to the level of < 0.1 °C could be used to decrease hour scale temperature fluctuations of the nanopositioners.

Mechanics

- *Status*: Current designs use a conventional coarse stage in parallel with a relatively massive weak-link fine stage for each motion axis [13]. While single axis motion may be less than 10 nm, this design maybe close to the positioning limit (10 – 25 nm) for multi-axis applications due to low frequency and unaccounted for dynamics and their effect on controllability. These dynamics are a direct result of the relatively massive structures.
- *R&D efforts*: We see two avenues of investigation. The first is to stay with the dual coarse/fine concept, but use an ultrasonic or linear motor for the coarse stage and use a light/stiff new design flexure for the fine stage. We are currently simulating highly damped, kinematic flexures and high-stiffness, over constrained flexures. The second avenue is a single stage approach. It may be possible to couple a custom ultrasonic motor stage with a high precision laser encoder. From the mechanics side, this approach is limited by the quality of motion guides. A variation on the

single stage approach is through a parallel kinematics (hexapod) arrangement. An overarching approach to our designs is to design devices with high first natural frequencies and to understand off-axis mechanism dynamics. Both of these qualities are important from the control design standpoint.

Actuation

- *Status*: Current designs use stepping motor actuated coarse stages and piezo stack actuated fine stages. The stepping motor stages are relatively large and massive. The range of a piezo stack actuator is limited to some tens of microns.
- *R&D efforts*: We see the piezo actuator as the primary candidate for dual stage approaches using novel flexures and also in the ultrasonic motor single stage approach. However magnetostrictive actuators may offer high forces to actuate very over constrained flexures, though power dissipation may be an issue. MEMS based electrostatic surface actuators and small hybrid electromagnetic actuators have potential for x-ray nanopositioning applications. These three actuation methods show promise in other fields [10] and we feel they should be considered for x-ray nanopositioning application. Thus, we are currently considering the pros/cons of these modalities.

Sensing

- *Status*: Current designs use a LDDM for linear displacement measurement. In a single-axis, prototype, the resolution was found to be .03 nm. This was achieved with twelve reflections between the target and the laser head. The principle of operation and the multipath approach necessitate a number of prisms to be mounted on the target. Current designs also employ capacitance probes for the measurement of rotation stage run out over small ranges.
- *R&D efforts*: We see the potential for improvement through the use of a LDV to replace the LDDM. The LDV has sub picometer resolution and according to the manufacturer, the LDV doesn’t require multiple passes or multiple prisms to achieve this result. The single path and simple retroreflector free up space and mass on the target stage. We are also considering the use of the LDV for a relatively long range measurement and capacitive sensors for measurement over a small range and then employing a relay sensing mechanism.

Controls

- *Status*: Current designs use a proportional-integral-derivative (PID) controller to feedback on differential position between the final optic and the sample position [13]. The effectiveness of this tracking control is limited by two fundamental constraints of feedback control [23]—as gain is increase the system becomes unstable due to shifting of the closed loop poles and the bandwidth or maximum frequency of actuation is limited by the location of the first system resonance. In addition, the mechanics of the current design are relatively massive and this can exacerbate the mentioned problems with PID control. The current approach is at or near the performance limit. Effective scanning operation is likely limited by the bandwidth limitation.

- *R&D efforts*: We see the need for change and opportunity for improvement in the control architecture used for x-ray nanopositioning. Higher bandwidth control (>200 Hz) is necessary for effective vibration control and exploitation of scanning operation. As mentioned, our mechanics will be designed with well damped, high first natural frequencies. However, this will be complemented with a controller that combines feedback control with model based feedforward control. In this architecture the feedforward controller is the inverted form of either an analytical or measured model of the closed-loop feedback positioner dynamics. The desired output is fed to the feedforward controller and the calculated input is fed to the PID feedback controller. The use of the inverted closed-loop system allows for higher control bandwidth and higher gain. In addition system hysteresis is compensated for. We feel that careful architecture design coupled with the use of commercially available controllers can achieve <1nm positioning resolution.

  Another control strategy we will investigate is the use of image or x-ray signal based sensing and control. Similar to x-ray microscopes, scanning tunneling microscope imaging performance may be limited by the first system resonance and encoding of a point other than the scanning tip. Image based sensing and control is seen as the path to subnanometer positioning accuracy [24]. In the x-ray microscopy application of this imaged-based control method, the distortions due to dynamic effects of the mechanics and control system will be quantified by making a reference image of a test article such as a Siemens star calibration pattern. The image distortions will be determined by comparing the known test pattern to the measured trajectory. The phase and phase errors in the scanning trajectory can be determined and used to compensate the scanning inputs for non-reference images. The image-based sensing and control approach will be tested with our previously developed 10 nm level positioner. While the path to x-ray microscopy using image based sensing and control is less defined then our other avenue of feedforward control, the potential for high positioning precision, higher speed, and reduced hardware complexity warrants the development work.

Funding Details

Cost: ($K)
Use FY08 dollars.

Year	AIP	Contingency
1	150	
2	75	
3	50	
4	50	
5	25	
6		
7		
8		
9		
Total	350	15%

Contingency may be in dollars or percent. Enter figure for total project contingency.

Effort: (FTE)
The effort portion need not be filled out in detail by March 28

Year	Mechanical Engineer	Electrical Engineer	Physicist	Software Engineer	Tech	Designer	Post Doc	Total
1	0.40			0.15		0.2		0.75
2	0.40			0.15		0.2		0.75
3	0.40			0.20		0.15		0.75
4	0.40			0.25		0.1		0.75
5	0.40			0.25		0.1		0.75
6								0
7								0
8								0
9								0

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Notes:

[1] **ICMS**. Check in first revision to ICMS as a *New Check In*. Subsequent revisions should be checked in as revisions to that document i.e. C*heck Out* the previous version and C*heck In* the new version. Be sure to complete the *Document Date* field on the check in screen.

[2] **Risk Assessment.** Advise of the potential impact to the facility or operations that may result as a consequence of performing the proposed activity. Example: If the proposed project is undertaken then other systems impacted by the work
include ... (If no assessment is appropriate then enter NA.)

[3] **Consequence Assessment.** Advise of the potential consequences to the facility or to operations if the proposal is not executed. Example: If the proposed project is not undertaken then ____ may happen to the facility. (If no assessment is appropriate then enter NA.)

[4] **Cost Benefit Analysis.** Describe cost efficiencies or value of the risk mitigated by the expenditure. Example: Failure to complete this maintenance project will result in increased total costs to the APS for emergency repairs and this investment of ___ will also result in improved reliability of ____. (If no assessment is appropriate then enter NA.)